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Achieving enhanced strength in ultrafine lamellar structured Al2024 alloy via mechanical milling and spark plasma sintering

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ABSTRACT

Recently, mechanical properties improvement through microstructure design has attracted worldwide attention. In the present study, a “bottom to up” route including mechanical milling and spark plasma sintering was employed for fabricating ultrafine lamellar structured Al2024 alloy. Microstructure observation revealed that flake shaped powder with a mean grain size of about 60 nm was obtained by mechanical milling for 20 h. The flake shaped powder self-assembled during sintering, forming a bulk sample with periodic lamellar structure and ultrafine grain size (1.14 µm). Tensile test revealed that the ultrafine lamellar structured alloy exhibited significantly enhanced strength (yield strength 375 MPa, tensile strength 456 MPa) compared to the conventional O-state counterpart, but the tensile ductility was reduced (tensile elongation 5%). Strategies for further optimizing the mechanical properties of the bulk samples were discussed.

1. Introduction

Aluminium and its alloys play an important role in modern society since they are most used non-ferrous materials. They have been widely used in automobile and aerospace industries as structural component due to their high specific strength, superior corrosion resistance and good machinability [1–3]. However, relatively low strength limits their further applications. During the last several decades, enormous work has been done to further optimize the mechanical properties (especially strength and ductility) of Al based materials.

According to the simple rule of mixture, introducing a hard phase in particulate form to a soft matrix could significantly increase the strength of the matrix. Accordingly, Al based metal matrix composites (AMMCs) containing various kinds of reinforced particles have been developed [4–6]. For example, Zheng et al. [4] have reported a compressive strength as high as 950 MPa in an Al-2024/20 wt% B_4C composites fabricated by a process including mechanical milling, hot compression sintering and subsequent hot extrusion. However, due to the remarkable difference in thermal expansion coefficient between the hard reinforced particles and the soft Al matrix, AMMCs always exhibit extremely low ductility/toughness [7], which could not satisfy the requirement for practical application as structural materials (usually tensile elongation larger than 5%).

Apart from introducing hard reinforced particles, microstructure design is believed as another effective strategy for improving the mechanical properties of metals without changing their chemical composition. Ameyama et al. [8–10] have proposed a so called “Harmonic Structure” design. The harmonic structure has a heterogeneous microstructure consisting of bimodal grain size together with a controlled and specific topological distribution of fine and coarse grains. The harmonic structure designed pure-Ti and SUS304 stainless steel exhibited a good combination of strength and ductility. However, the “Harmonic Structure” has not yet been realized in Al alloys. Recently, nanolaminate architecture design which is learned from nature (such as nacre) also become a popular modal for mechanical properties optimization [11–14]. Sun et al. [11] reported that an enhanced flexural strength could be obtained in a multi-layered Ti/Ti-Al intermetallics fabricated by hot compression sintering using pure Al and Ti foils. Jiang et al. [12] reported an enhanced tensile properties in an Al_2O_3/Al biomimetic nanolaminated composites through so called “flake powder metallurgy” approach. The similarity of the above techniques is that they all employ a “bottom to up” processing route. In other words, the desired structural unit was firstly prepared and then assembled into bulk specimens via various methods.

Powder metallurgy (PM) is a simple and scalable “bottom to up” approach, by which microstructure and mechanical properties of

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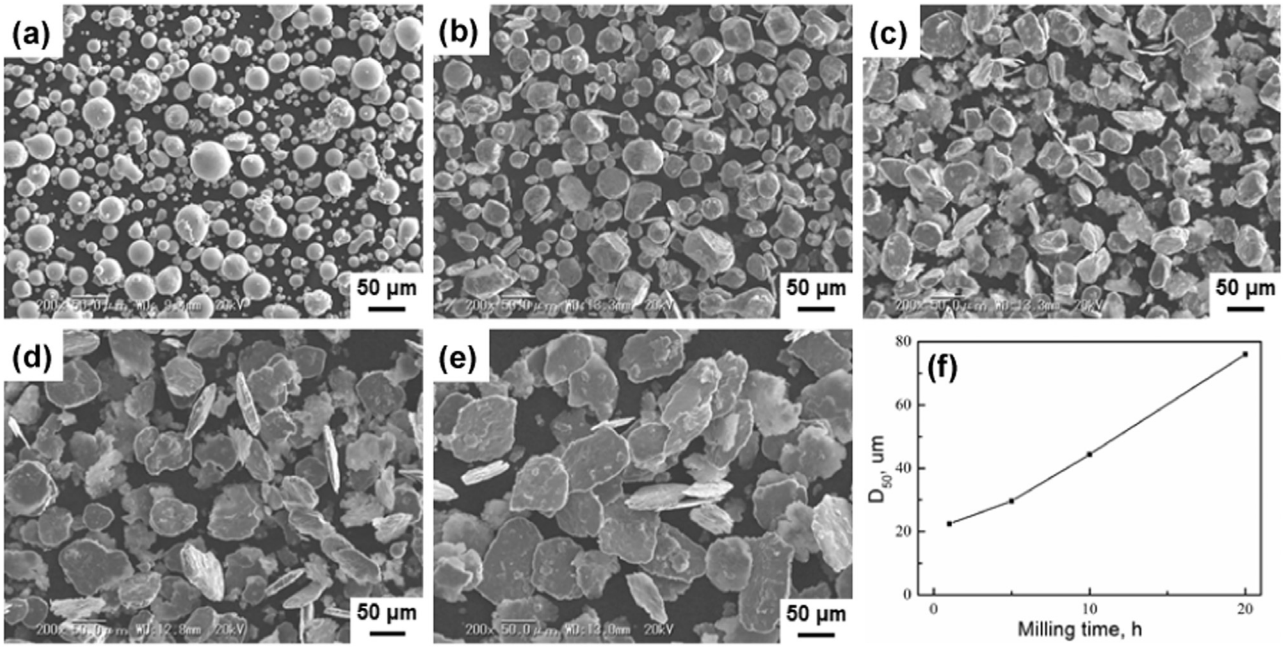

Fig. 1. Morphology of the (a) as-atomized Al2024 powder and the powder milled for (b) 1 h, (c) 5 h, (d) 10 h and (e) 20 h. The mean particle size as a function of milling time is shown in (f).

materials could be adjusted in a wide range [15–17]. Normally, PM is a two-step method consisting of mechanical milling of powders and subsequent consolidation. During mechanical milling, powder particles were trapped by the grinding media (usually stainless steel balls). The force of the impact plastically deforms the powder particles leading to work hardening and fracture. By adjusting the milling parameters (such as speed, time and process control agent), powders with various kinds of apparent morphologies and internal microstructures could be obtained. Then the milled powders could be consolidated through a variety of ways, such as hot pressing (HP), hot isostatic pressing (HIP) and more recently spark plasma sintering (SPS). SPS is a relatively new technology capable to sinter materials at lower temperature and in a shorter cycle time than other sintering processes [18]. Moreover, it is believed that the high pulsed current density can generate localized micro-plasmas into the gaps or at the contact points between metallic powder particles, which can clean the powder surface and breakdown the oxide layer.

In the current study, PM routes including mechanical milling and subsequent SPS was used for fabricating ultrafine lamellar structured Al alloy. A commercial Al-Cu-Mg alloy (Al2024) powder was selected for realizing the idea. The effect of milling time on the evolution of powder morphology and microstructure was investigated. The sintering parameters was determined by our previous study [19]. Room temperature tensile test revealed that enhanced tensile strength and acceptable ductility were obtained in the ultrafine lamellar structured Al2024 alloy.

2. Experimental

2.1. Mechanical milling of Al2024 powder

Commercial gas atomized Al2024 alloy powder with Cu (~4.2 wt%) and Mg (~1.5 wt%) as the primary alloying elements was used as the starting material. The mechanical milling experiment was conducted using a Fritsch pulverisette 5 high-energy planetary milling apparatus. The SUS 304L milling tank and balls were selected as the milling medium. Milling parameters were selected as follows: ball to powder ratio 10:1, rotation speed 200 rpm, total milling time 20 h, with argon atmosphere protection. To prevent adhesion and welding of the powder to the tank walls and the balls, and to control the fracturing events, 2 wt% stearic acid ($CH_3(CH_2)_{16}COOH$) was added as a process control agent (PCA). After mechanical milling, the tank was opened in an argon-protected glove box and the powders were quickly transferred into a graphite die for subsequent sintering process.

2.2. Sintering of the powders

The consolidation of the samples was made using a Sumitomo model 1020 SPS apparatus. The SPS experimental setup used in this study consists of a graphite die containing the sample and two punches. The punches are 15 mm in diameter and 25 mm long. The samples were heated to 500 °C at a heating rate of 100 °C/min with a pressure of 50 MPa. The sintering holding time was 10 min. For comparison purpose, the sample made from un-milled Al2024 powder was also sintered by the same parameters.

2.3. Microstructure and mechanical properties evaluation

Powder size distribution was examined by using a SHIMADZU SALD-2300 laser diffraction particle size analyzer. X-ray diffraction (XRD) analysis was carried out using a RIGAKU RINT-2000 X-ray diffractometer using Cu Kα radiation. Powder morphology evolution and microstructure of the bulk samples were examined by a scanning electron microscope (SEM) JSM-6010. The grain size evaluation was performed on bright and dark field micrographs conducted on a JEM-2100F transmission electron microscope (TEM) operating at 200 kV. The energy dispersive spectrometer (EDS) and electron backscattering diffraction (EBSD) measurements were carried out in a JSM-7100F SEM. TSL OIM software was used for analyzing EBSD data.

The mechanical properties of the bulk samples were characterized by room temperature tensile test using a SHIMAZU AGS-10kND universal testing machine. All of the samples were cut and polished into dog-bone-shaped specimens with a gauge length of 3 mm and a cross section of 1 mm×1 mm. The operation of the testing machine was computer-controlled and the digital data of load and displacement from the gauge section were recorded. Tensile test was performed at a